Fracture Stimulation Field Demonstration Projects[1]

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Abstract

In 1994 the U.S. Department of Energy, Morgantown Energy Technology Center (DOE/METC) initiated a field R&D project entitled "Field Verification of New and Novel Fracture Stimulation Technologies for the Revitalization of Existing Underground Gas Storage Wells". The purpose of the project is to demonstrate the application of various hydraulic and pulse fracturing technologies (including tip-screenout fracturing, hydraulic fracturing with liquid CO_2 and proppant, extreme overbalance fracturing-EOB, and high energy gas fracturing) as techniques to enhance the deliverability of existing gas storage wells and fields. The impetus behind the initiative is to assist the gas storage industry maximize asset utilization via new deliverability-enhancing technologies that can mitigate the persistent 5% per annum deliverability decline in a cost-effective manner. Fracturing holds considerable promise in this regard, being a potentially more effective and sustainable stimulation approach than currently utilized well enhancement methods (e.g., reperforating, acidizing, mechanical scale removal, etc.), and also being more cost-effective than drilling replacement injection/withdrawal wells. Historically, however, the gas storage industry has been reluctant to utilize fracturing over concerns of caprock damage and bottom liquids encroachment.

To address these important concerns and accomplish the project objective, various fracturing technologies are being carefully demonstrated and compared to traditional well enhancement methods at nine test sites across the country. Detailed site characterizations, treatment design studies and fracture diagnostics are being conducted at each site to ensure successful implementation and understanding of the treatment results and benefits. To date (first quarter, 1997) operations are underway at five sites testing tip-screenout, liquid CO_2 and EOB fracturing. This paper describes those results and demonstrated benefits of fracturing at three of these sites.

The first site, the Galbraith Field located in Jefferson County, Pennsylvania, three previous hydraulic fracturing treatments using a gelled water fracturing fluid resulted in substantial deliverability enhancements. However, lengthy fracture fluid cleanup times were experienced (a common occurrence in those fields where fracturing is performed in the gas storage industry) suggesting that a low-damage fracturing fluid, such as liquid CO_2, could provide similar but more

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immediate benefits. Three such treatments were subsequently performed at the site, with one failing due to mechanical problems. For the two successful treatments, an average folds-of-increase in deliverability of six was immediately achieved, three times better than comparable information for the gelled water treatments. From a cost standpoint, the cost of added deliverability in $/Mcfd for the liquid CO_2 treatments was half that for the earlier gel treatments. Hence this project successfully demonstrated that a low-damage fracturing fluid system, such as liquid CO_2, can successfully provide immediate tangible well stimulation benefits to the gas storage industry.

The second test site is the Huntsman Field in Cheyenne County, Nebraska. Here the operator was seriously concerned about fracture height growth upward through the overlying caprock, as well as downward into a bottom-liquids column. Further, the high formation permeability necessitated that any fracture treatment should achieve a high fracture conductivity. This suggested the application of a short tip-screenout fracture. Following a careful treatment design and fracture diagnostics program, the first treatment was successfully implemented. Subsequent fracture diagnostics and deliverability testing has shown that the hydraulic fracture grew as anticipated, most importantly not through the over/underlying formations, and has provided an immediate improvement in deliverability of almost 50%. Considerable additional improvement is expected with further fracture fluid cleanup. Based on those results, the operator has agreed to proceed with the remaining two treatments. This project successfully demonstrated that with careful design engineering and up-front diagnostics, fracturing can be effectively employed in settings where there is little tolerance for upward/downward fracture growth.

The final test site presented in this paper is the Donegal Field in Washington County, Pennsylvania. Prior well enhancement efforts at the field, including a reperforation campaign and tip-screenout fracturing, yielded little to marginal results in the way of deliverability improvement. Through rock mechanics and fracture modelling studies it was concluded that the best opportunity for well stimulation via fracturing was with EOB technology. EOB treatments were subsequently shown to successfully provide fracture coverage across the entire storage horizon, previously not possible with hydraulic fractures which tended to grow horizontally. A breakthrough computer model to simulate the EOB process was also developed as part of this project, providing new insights into key treatment parameters and optimization procedures.

Introduction

An improved, more efficient natural gas storage system is essential for supporting the growth in US gas demand in the coming decades. A high priority therefore exists to increase current domestic storage capability and offset the persistent 5.2% average annual loss in well deliverability from gas storage fields[1]. Although storage field operators have extensive experience with current well remediation technology, recently published case studies demonstrate the shortcomings of traditional, non-fracturing well revitalization methods[2,3]. In 1994, CNG Transmission fracture-stimulated 30 wells in five Oriskany gas storage fields using conventional techniques, demonstrating that highly encouraging results can be achieved with fracturing[4]. However, there still remains considerable potential for using new and novel fracture stimulation technologies to restore injection and withdrawal capabilities in gas storage wells where conventional fracturing may not be applicable, for example where fracture fluid sensitivities and height growth concerns exist, and also in high-permeability reservoirs[5]. Thus a comprehensive evaluation of alternative fracture stimulation techniques is required to demonstrate that certain technologies can be effectively applied to increase well deliverability in these settings.

In response to this industry need, DOE/METC has initiated this multi-year field program designed to demonstrate the application of new and novel fracturing technologies to revitalize deliverability from existing gas storage facilities and wells. The demonstration of these techniques, in cooperation with industry partners, should serve to promote and accelerate the transfer of the most promising of these technologies to the industry at large, thus making a direct, immediate and positive impact on mitigating the industry-wide problem of deliverability decline.

The RD&D program calls for the demonstration of as many as five different fracturing technologies at nine different field locations during a three year period. Three wells are to be stimulated with a new and novel technology at each test site. The five different technologies are:

- Tip-screenout hydraulic fracturing
- Liquid CO_2 with proppant hydraulic fracturing
- Gaseous nitrogen hydraulic fracturing
- Propped nitrogen pulse fracturing (extreme overbalance)
- High energy propellant gas fracturing

In 1995, the first three test sites were selected. This paper presents the results and status of these three sites; the Galbraith Field in Pennsylvania operated by National Fuel (liquid CO_2 with proppant fracturing), the Huntsman Field in Nebraska operated by KN Energy (tip-screenout fracturing) and the Donegal Field, also in Pennsylvania, operated by Columbia Gas (tip-screenout and extreme overbalance fracturing).

Results and Discussion

Liquid CO_2 Fracturing - Galbraith Test Site

Site Description. The Galbraith field is located in Jefferson County, Pennsylvania. Figure 1 shows the Galbraith location. It was discovered in 1917 in the Devonian First Sheffield Sandstone at an average depth of 2,800 feet (ft). Originally a gas reservoir, Galbraith was depleted and converted to storage operations in 1937. The field now has 26 injection/withdrawal wells. Due to the age of the wells, drilling, completion and workover information is limited. The selected technique for Galbraith was hydraulic fracturing with liquid CO_2 and proppant. The selection was made after observing evidence of long cleanup times for previous water-based fracturing treatments at Galbraith. The deliverability plot in Figure 2 illustrates the long-term cleanup effects for Galbraith well No. 4139. The three wells selected for liquid carbon dioxide fracturing were numbers 2960, 4886 and 4936.

Galbraith Technical Discussion. Based on the data collected, a preliminary design for propped liquid CO_2 fracturing at Galbraith was prepared. The most critical design considerations were the maximum in-situ sand concentration that could be achieved, and high fluid leakoff caused by higher than expected formation permeability and the low viscosity of liquid CO_2. Physical limitations such as the maximum possible pump rate and volume of sand contained within the liquid CO_2 blender were also considered in the design. The preliminary design, which called for 26,000 gallons (gals) of liquid CO_2 and 15,000 pounds (lbs) of 20/40 proppant, was developed to achieve a 70 foot fracture half-length with a conductivity of 5000 md-ft. Modelling results indicated a high probability for an early screenout.

In October 1995, the first treatment was performed on well 4886. The sand schedule for the job called for a low initial sand concentration. However, a slug of sand estimated at 3 ppg concentration entered the well at the start of the sand schedule. Shortly after this sand slug reached the perforations, pump pressure rapidly increased and the job was terminated. An estimated 2,800 lbs of sand was placed in the formation, much less than the job design. The second well, 4936, was also stimulated in October 1995. This time, the initial low concentration sand stage was pumped successfully. However, shortly after frac fluid with one pound per gallon sand concentration reached the perforations, pump pressure rapidly increased and the job was terminated.

Based on the execution of the first two stimulations, the job design for the third well was modified. Pad volume was increased and a higher pump rate of 60 barrels per minute (bpm) was set as an objective. Smaller proppant was also desired, but unavailable. The use of pre-frac formation breakdown treatments were also considered to lower pumping pressures, but this idea was discarded in order to maintain as clean and non-damaging a stimulation fluid as possible.

The third well, 2960, was stimulated in November 1995. The job was interrupted by several equipment related and unplanned shutdowns. As pumping of the pad volume was completed, a shutdown of 10 minutes occurred. During this time, wellhead pressure declined to the normal shut-in pressure, suggesting that the entire pad volume had leaked off and the hydraulic fracture had closed. Due to the limited volume of liquid CO_2 on the job site, sand was added to the injection fluid soon after pumping resumed. However, pressure rose as soon as the sand reached the perforations and the job was terminated. It was estimated that less than 500 lbs of sand was actually placed in the formation.

An important component of the R&D program was to perform pre- and post-treatment pressure transient tests such that the benefits of the restimulation could be measured in terms of deliverability improvement and skin factor changes. The test results for each of the wells is provided in Table 1. In the cases of wells 4886 and 4936, significant reductions in skin factors were achieved as a result of the restimulations leading to folds-of-increase in AOF of six to seven. Well 2960, however, while exhibiting a reduction in skin factor, also appeared to have a lower permeability and a lower deliverability.

A final requirement of the R&D program is to perform follow-up testing one year after the stimulation to evaluate the degree to which any deliverability improvement can be sustained. This testing is anticipated to be performed in the spring of 1997.

Benefits of the Technology. The successfully executed liquid CO_2 stimulations showed an immediate and dramatic 6-fold improvement in well deliverability. These results compare favorably with data from well 4139 which was fractured using a gelled water treatment, as shown in Table 2.

The 4139 frac job produced only an immediate 2.1 fold of increase. This favorable comparison can also be made on $/unit cost basis; the liquid CO_2 stimulations were more cost effective in terms of $/Mcfd of improved deliverability as well as in terms of $/percent improvement. Although the liquid CO_2 stimulations are initially more expensive, their superior performance appears to more than justify the added cost. Note, however, that this comparison in cost effectiveness is made without the benefit of permeability and skin estimates for well 4139. Nevertheless, the attributes of liquid CO_2 fracturing make it particularly well suited for use in gas storage wells which develop very low water saturation after many years of service. The use of liquid CO_2 does not increase the near-wellbore water saturation.

Based on these results, it is apparent that fracturing with liquid CO_2 and sand can effectively stimulate gas storage wells. Fracture fluid cleanup is immediate as well as reservoir response. The cost of the immediate added deliverability created by liquid CO_2 fracturing can be attractive compared to other fracturing techniques.

Tip-screenout Fracturing - Huntsman Test Site

Site Description. The Huntsman Storage Unit is located in Cheyenne County, southwestern Nebraska (Figure 1). The Unit is comprised of the Huntsman, West Engelland, and Gurschke Fields with a total of 18 injection/withdrawal wells (Figure 3). The Huntsman Field is used for both injection and withdrawal; the West Engelland Field is only used as a withdrawal site. The Gurschke Field is inactive.

Huntsman was first discovered in the 30 ft Lower Cretaceous "J" sand at a depth of about 4,800 feet in December, 1949. KN Energy acquired the most important sections of the Huntsman storage unit in 1963 and converted it to a storage reservoir.

The primary concern whether tip-screenout hydraulic fracturing could be applied at Huntsman was the potential for fracture height growth up through a shale barrier overlying the storage horizon. The operator felt that the application of any fracture technology should be designed for minimal height growth.

Huntsman Technical Discussion. Due to these concerns over possible fracture height growth, a considerable level of diagnostics were employed to design and evaluate the treatment results for the first well prior to proceeding with the subsequent two. These diagnostics included two mini-fracs (radioactive tracers were run in both and a temperature log was run after the second to identify possible fracture height growth), and radioactive tracers were included (for both liquid and proppant) during the main treatment for the same purpose. Fracture modelling was also employed as a diagnostic tool.

The mini-fracs were performed on the first test well, HS-23, in March 1996. As shown in Figure 4, the post-mini-frac gamma ray logs indicated almost perfect fracture containment based on the radioactive tracers. However the temperature log run after the second mini-frac and shown in Figure 5 indicated fracture penetration possibly to the top of the overlying shale. Fracture modelling suggested limited height penetration into the shale. The consensus of the project team was that there was a high probability that the main treatment could be pumped without fracturing through the caprock. However, achieving a quick screenout to arrest fracture extension was imperative to treatment success.

The main treatment was pumped in April 1996. However, a larger pad than designed was pumped, delaying the onset of a tip-screenout. The treatment was therefore terminated early to avoid continued fracture height growth prior to a tip-screenout. In total, 10,000 lbs of proppant were placed.

Post-treatment fracture modelling indicated some height growth, about half-way through the shale (Figure 6). A post-treatment multiple-isotope tracer log showed tracers in the "J" sand with little indication of fracture penetration into the Huntsman shale (Figure 7). After a short period of post-frac cleanup, the well was put into service for the summer injection season.

Similar to the Galbraith Field, the R&D program requires that multi-point deliverability and pressure transient tests be performed on each of the test wells before fracturing, after fracturing and again one year later. Results from the tests are provided in Table 3.

After the summer injection season, the HS-23 was pressure transient tested to determine its post-frac condition. Results, also shown in Table 3, were consistent with expectations. The short clean-up period after the stimulation followed by injection season limited the amount of fracturing fluid produced back to the surface. This is reflected in the somewhat lower value for relative permeability to gas. Also, the premature termination of the frac job is reflected in the modest improvement in skin. Nevertheless, the well shows a nearly 50% improvement in deliverability with further cleanup probable when well production resumes during the winter season. Based on these encouraging results, the operator has elected to proceed with fracturing the next well in the program.

Fracturing of the second well, HS-45, is scheduled for spring 1997. After approximately a one month observation period, including a post-fracturing pressure transient test, final scheduling will be made for the third well so that it can also be fractured this spring while reservoir pressure is still near its annual minimum. Finally, pressure transient tests will be performed one year after the treatments to evaluate the longer term deliverability improvements achieved.

Benefits of the Technology. Based on the Huntsman results, it has been demonstrated that fracture diagnostics, including the use of mini-frac procedures, radioactive tracers, temperature surveys and three-dimensional fracture modeling, are invaluable for predicting the potential for fracture height growth. By incorporation of the results of fracture diagnostics into the final job design, tip-screenout fracturing can be successfully applied in formations where height growth control is important and fracturing technology may have otherwise been avoided.

Tip-screenout and EOB Fracturing - Donegal Test Site

Site Description. As indicated in Figure 1, the Donegal Field is located in Washington County, Pennsylvania. Discovered in 1907, this depleted gas reservoir was converted to storage operations in 1940. Depth to the top of the Gordon Stray sandstone in the Donegal Field is about 2,600 feet.

Total thickness averages 30 feet with a net pay of 8 to 10 feet. The field has a total of 112 injection/withdrawal wells and 4 observation wells.

Donegal Technical Discussion. Operator preference was to perform tip-screenout fracturing at this test site since they had previously attempted a tip-screenout treatment in the field. Detailed fracture modelling analysis of that treatment indicated the possibility that a horizontal fracture had been created. This appeared to be substantiated by a post-frac radioactive tracer survey from the well.

A series of fracture diagnostics tests, including a breakdown test, a step-rate test, a step-down test, and a mini-frac were performed on well 4003 in June 1996. The data again suggested the creation of a predominantly horizontal fracture. A new and novel treatment was therefore designed to create a horizontal tip-screenout to divert proppant-laden slurry into a short vertical fracture near the wellbore. The design called for the placement of 37,000 lbs of 20/40 proppant with 14,000 gals of linear gel at 12 bpm.

The main treatment was pumped in July 1996. While the proppant and fluid volumes were essentially pumped according to the design schedule, no screenout was observed. The radioactive tracer survey carried out after the job, shown in Figure 8, indicated several sharp tracer concentrations, including at the top and base of the formation. It was apparent that a vertical fracture was not created and this raised serious doubt that tip-screenout fracturing could be effectively applied at this site.

Based on these results, the operator and the contractor decided to attempt a different stimulation technique. To achieve relatively short vertical fractures in the storage horizon that would extend beyond formation damage, the adverse in-situ stress conditions had to be overcome. The decision was made to attempt extreme overbalance fracturing techniques.

A nitrogen perforation surge treatment was designed for the second well at the test site, number 4053. The stimulation was performed in August 1996. A total of 380 gallons of liquid were loaded into the well and injected into the reservoir by using compressed nitrogen which was suddenly released by a rupture disk set to yield at 4330 psi. Results of the radioactive tracer survey run after the job, shown in Figure 9, indicate an entirely different distribution of tracer material than seen from hydraulic fracturing, and suggest the entire reservoir sand was stimulated.

Although the 4053 EOB stimulation was successful, other similar treatments at Donegal failed to breakdown the formation. To model the execution of the 4053 stimulation and improve the design for subsequent wells, new software was developed specifically for this purpose. This allowed simulation of the 4053 EOB fracturing in a manner similar to traditional hydraulic fracturing software. Through simulation, the determination was made that the EOB treatments, as designed, were able to generate rates and pressures that were just at the threshold necessary to fracture the formation. Small simulated variations in rock properties or treatment design were sufficient to prevent formation breakdown.

Pressure transient testing requirements at this site are similar to those at the Galbraith and Huntsman fields. Results of the pre- and post-stimulation tests for each of the test wells are provided in Table 4.

Although results of post-frac testing of well 4003 do not show an immediate improvement in skin condition, they are expected to improve with fracture fluid cleanup as did the previous hydraulically fractured well, 4019. The comparison is made in Table 5. Note that well 4003, fractured in June, was subsequently placed on injection which hindered fracture fluid cleanup whereas well 4019, fractured in September, was not subject to a similar condition. These data from the stimulations and the tracer surveys further indicate that hydraulic fracturing is not particularly effective at Donegal. However, later testing should show continued long-term clean-up effects for 4003, as was the case for 4019.

For well 4053, the post-frac test was performed after a very short clean-up period. As shown in the well's deliverability plot, Figure 10, the well is actively cleaning up. Each successive flow period of the 4 point isochronal test showed improved skin and deliverability. Long-term performance of the 4053 is yet to be determined.

Design work for the EOB stimulation of the third well is in progress, using the new software. Once approved, the job can be scheduled, probably for the summer, 1997. Post-stimulation pressure transient testing of the third well and one-year testing of all three wells also remains.

Benefits of the Technology. In-situ stress conditions favor the creation of horizontal hydraulic fractures which do not appear to provide acceptable performance improvement Extreme overbalance fracturing may be an effective alternative in these adverse stress conditions. EOB techniques appear to have the ability to create vertical fractures where hydraulic fracturing was unable to.

The use of advanced fracture diagnostics and simulation accurately predicted that effective hydraulic fracturing would be difficult to achieve at the Donegal Test Site. This demonstrates the value of these diagnostics, without which the contribution of a sub-optimal stimulation program would have occurred.

Application of a "new and novel" technique, extreme overbalance, demonstrated that stimulation of formations that resist more conventional techniques is possible. To ensure that the "new and novel" technique is effectively applied, new software was developed to improve the design of EOB stimulations. This new development can be applied to jobs of this type throughout the industry.

Project Conclusions

Based on the results of this project so far, the following interim conclusions can be drawn:

- Liquid CO_2 fracturing appears to be effective in providing immediate and significant improvements in gas storage well deliverability. It is apparent, however, that the ability to achieve high injection rates is a critical factor to proppant placement volume. This need may be particularly prevalent in high permeability settings where fluid leakoff is expected to be significant.

- Tip-screenout fracturing is ideally suited for restimulating high permeability gas storage horizons, particularly where fracture height growth is a concern. Precise treatment design, is a requirement for successful implementation. This includes giving due consideration to rock mechanical properties and in-situ stresses. Effective fracture fluid cleanup may also be an important success factor.

- Pre-stimulation testing and fracture design studies can be used to determine the likelihood and risk of fracture height growth. In the case of the Huntsman Field, a fracture treatment would not have been attempted without a thorough diagnostics program to fully understand the potential for height growth, and appears to have predicted the outcome reasonably well.

- Extreme overbalance techniques can be applied to gas storage horizons, particularly in areas unfavorable for other stimulation techniques. However, thoughtful design is necessary to maximize effectiveness and application of specialized software is recommended.

Acknowledgments

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TABLE 1-COMPARISON OF PRE- AND POST-FRACTURE TEST RESULTS, GALBRAITH TEST SITE				
Well No.	**4886**	**4936**	**2960**	**Total**
Pre-Stimulation Condition:				
Permeability, md	231	23.1	521	
Skin	+55	+31	+65	
AOF 675 psia, mmscfd	2.3	0.6	5.3	8.1
Post- Stimulation Condition:				
Permeability, md	235	25.5	220	
Skin	+1.5	-2.2	+37	
AOF 675 psia, mmscfd	13.2	3.9	3.7	20.9
Folds of Increase	5.8	6.9	0.7	2.6

TABLE 2-COMPARISON OF GEL AND CO_2 FRAC RESULTS		
Well No.	**4139***	**4886/4936 Average****
Frac Fluid	Gelled Water	Liquid CO_2
Pre-Frac AOF, mmscfd	0.700	1.429
Post-Frac AOF, mmscfd	1.500	8.581
AOF Improvement, mmscfd	0.800	7.152
Folds-of-Increase	2.1	6.0
Treatment Cost	$16,200	$47,300

* Only well with same-year pre/post test data
** Successful efforts

TABLE 3-PRE- AND POST-FRACTURE TEST RESULTS, HUNTSMAN TEST SITE			
Well No.	**HS-23**	**HS-25**	**HS-45**
Permeability, md	45.0	105	695
Skin	+4.4	0	+18.9
AOF 1182 psia, mmscfd	34.9	78.2	147
Post-Stimulation Condition			
Permeability, md	36.0		
Skin	+0.1		
AOF	51.2		
Folds of Increase	1.5		

TABLE 4-PRE- AND POST-FRACTURE TEST RESULTS, DONEGAL TEST SITE			
Well No.	**4003**	**4053**	**12155**
Permeability, md	27.0	53.5	34.5
Skin	+0.4	-0.2	-0.1
AOF 1275 psia, mmscfd	6.5	8.9	8.6
Post-Stimulation Condition			
Permeability, md	27.0	50.0	
Skin	+16	+3.0	
AOF 1275 psia, mmscfd	2.0	4.7	

TABLE 5-PRE/POST-FRACTURE TEST RESULTS DONEGAL TIP-SCREENOUT WELLS			
	Pre-Stimulation	**Post-Stimulation**	**One-Year Later**
Well 4003			
Permeability, md	27.0	27.0	-
Total Skin	+0.4	+16	-
AOF 1275 psia, mmscfd	6.5	2.0	-
Well 4019			
Permeability, md	27.5	22.4	38.0
Total Skin	+14.4	+9.3	+3.0
AOF 1275 psia, mmscfd	2.2	2.5	6.5

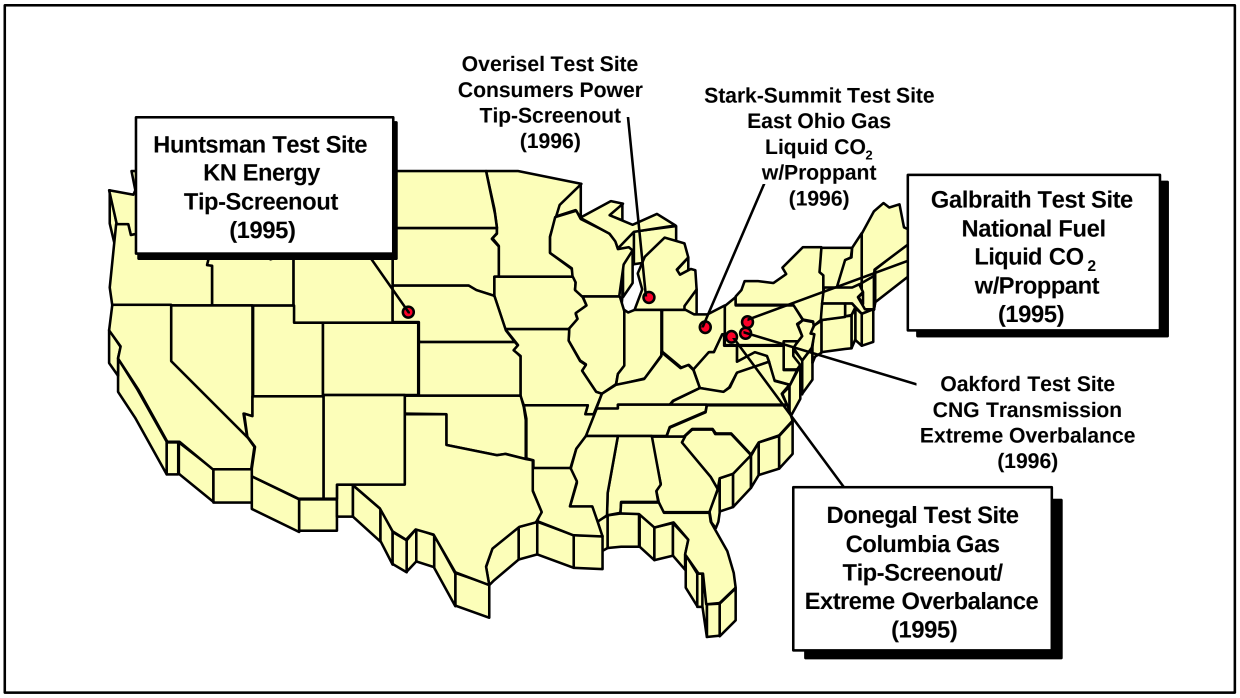

Figure 1. Location of Test Sites

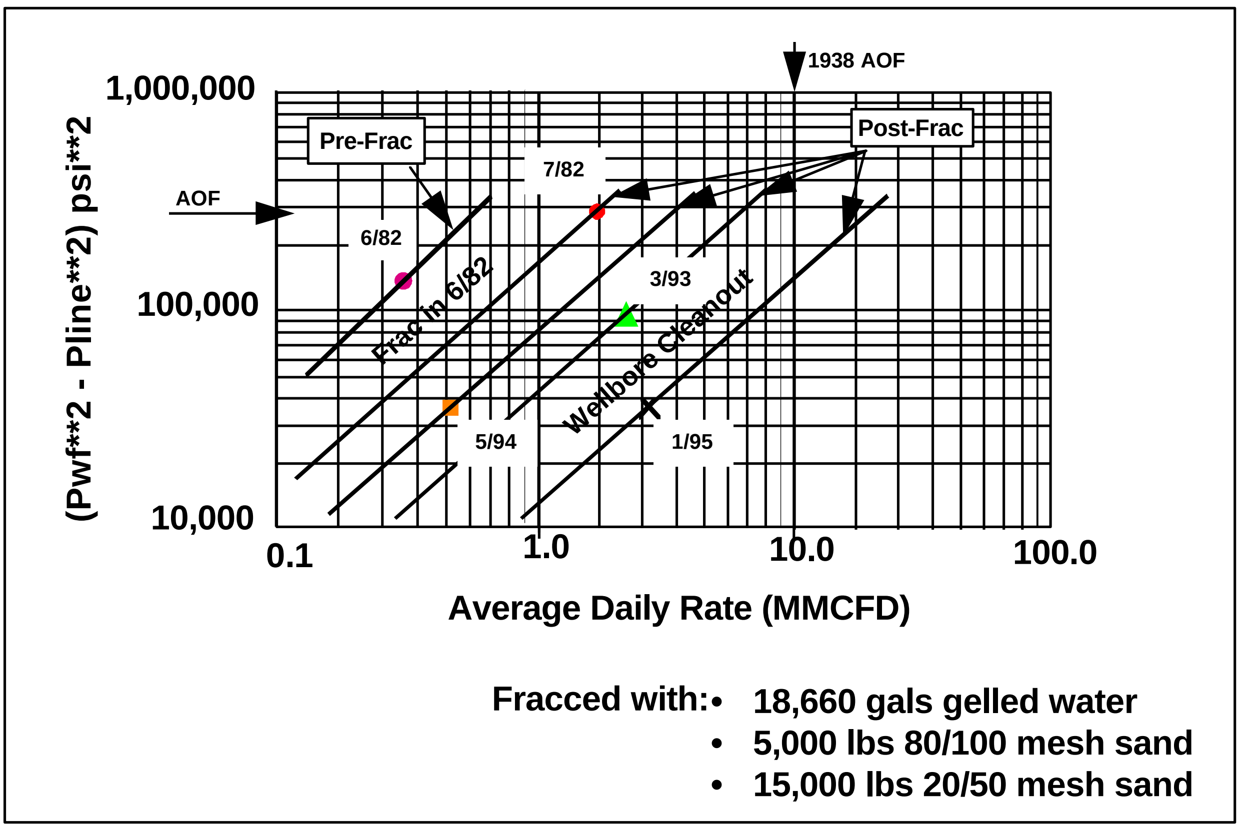

Figure 2. Well #4139 Wellhead Deliverability
(Pre- vs. Post-frac)

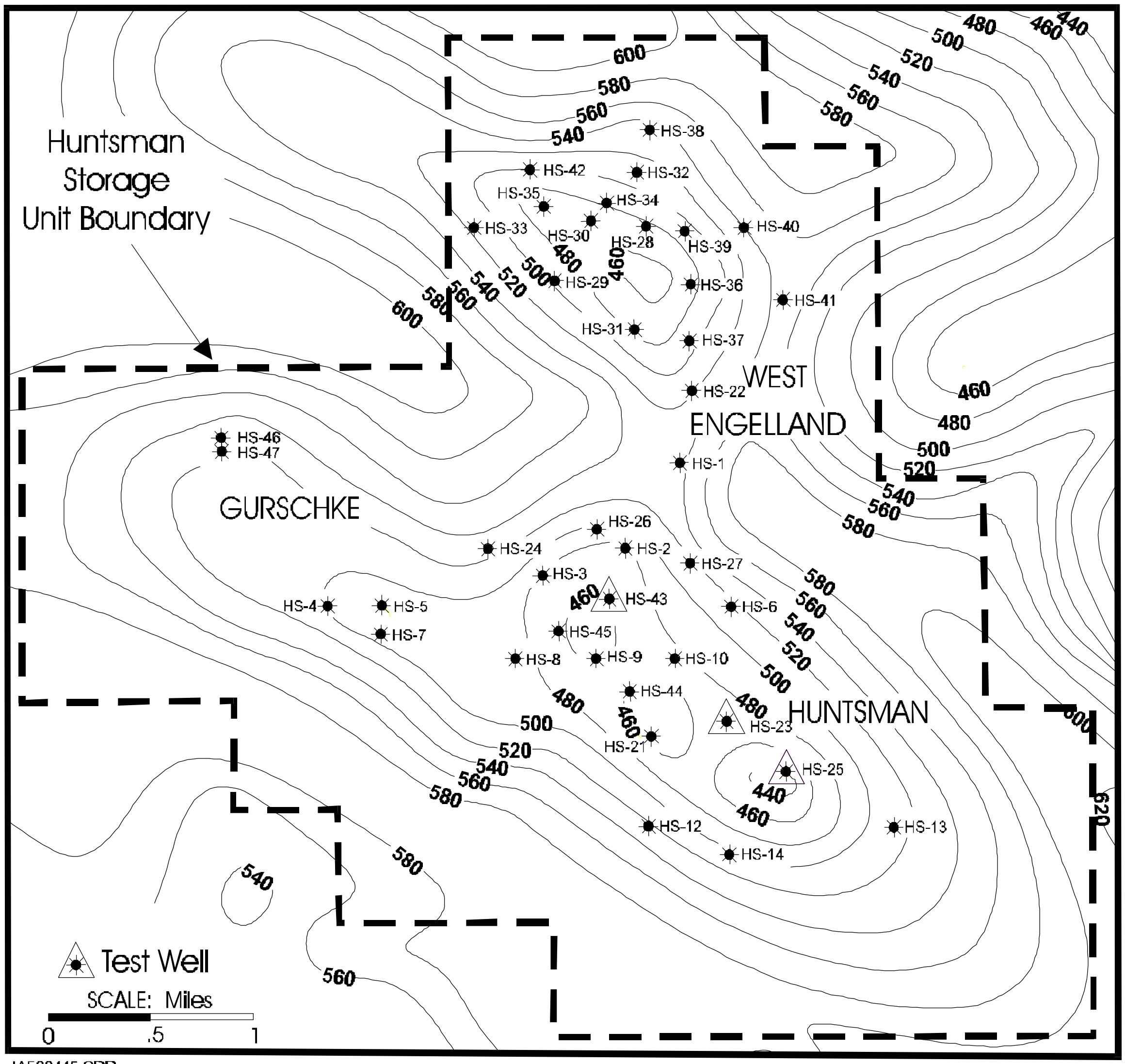

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Figure 3. Structure Map of the Huntsman Storage Unit

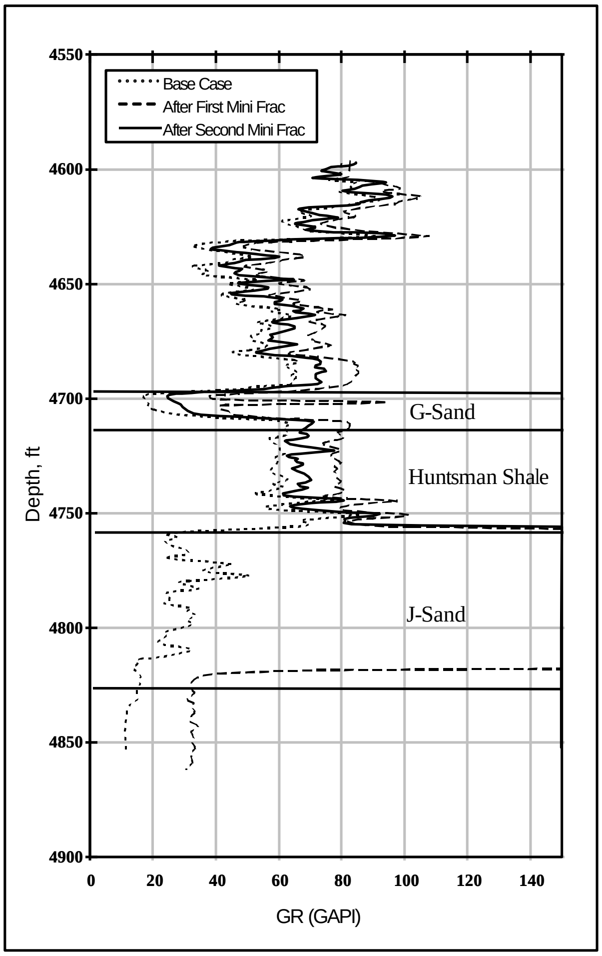

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Figure 4. Post-Mini-Frac Gamma Ray Logs, Huntsman HS-23.

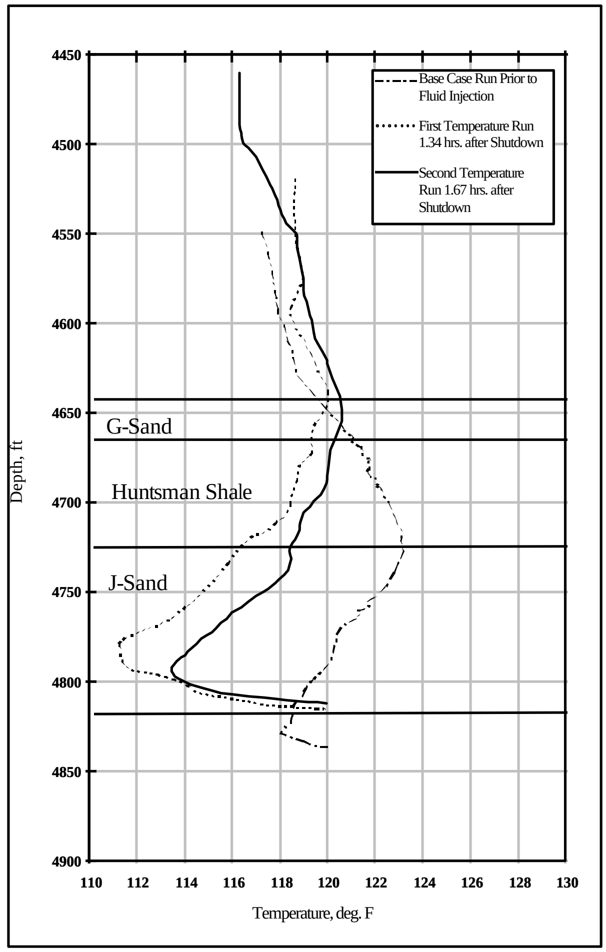

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Figure 5. Temperature Log After Second Mini-Frac, Huntsman HS-23.

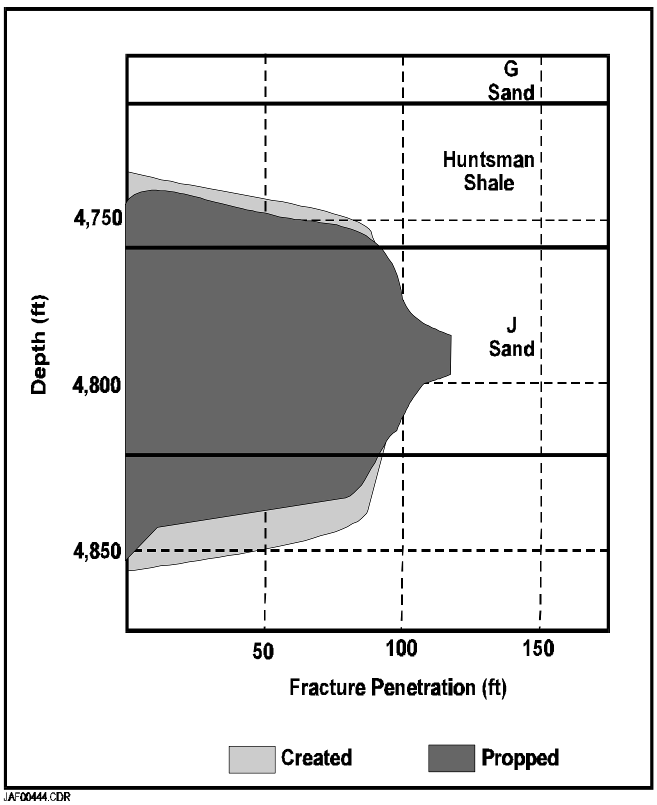

Figure 6. Modelled Fracture Geometry, Huntsman HS-23

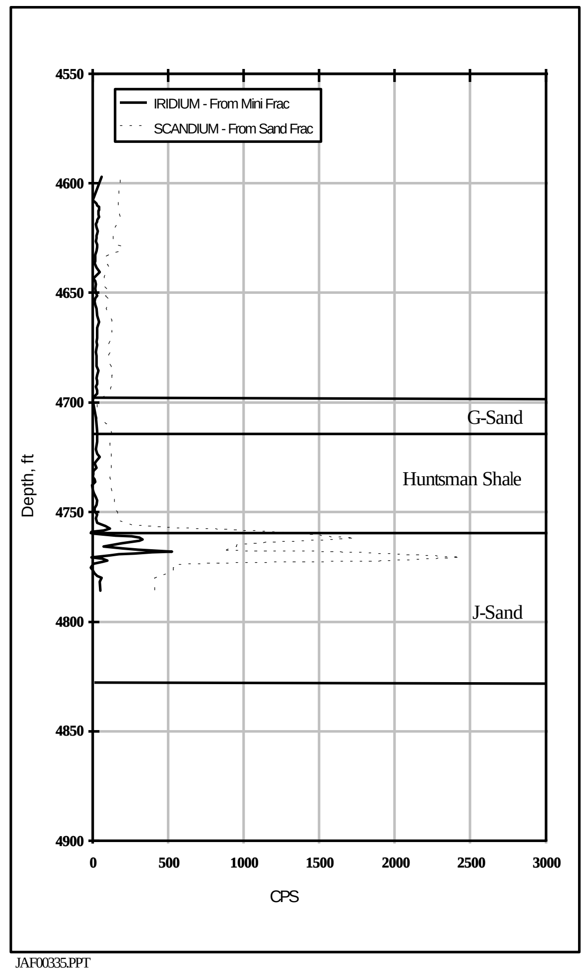

Figure 7. Post-Stimulation Multiple-Isotope Tracer Log, Huntsman HS-23

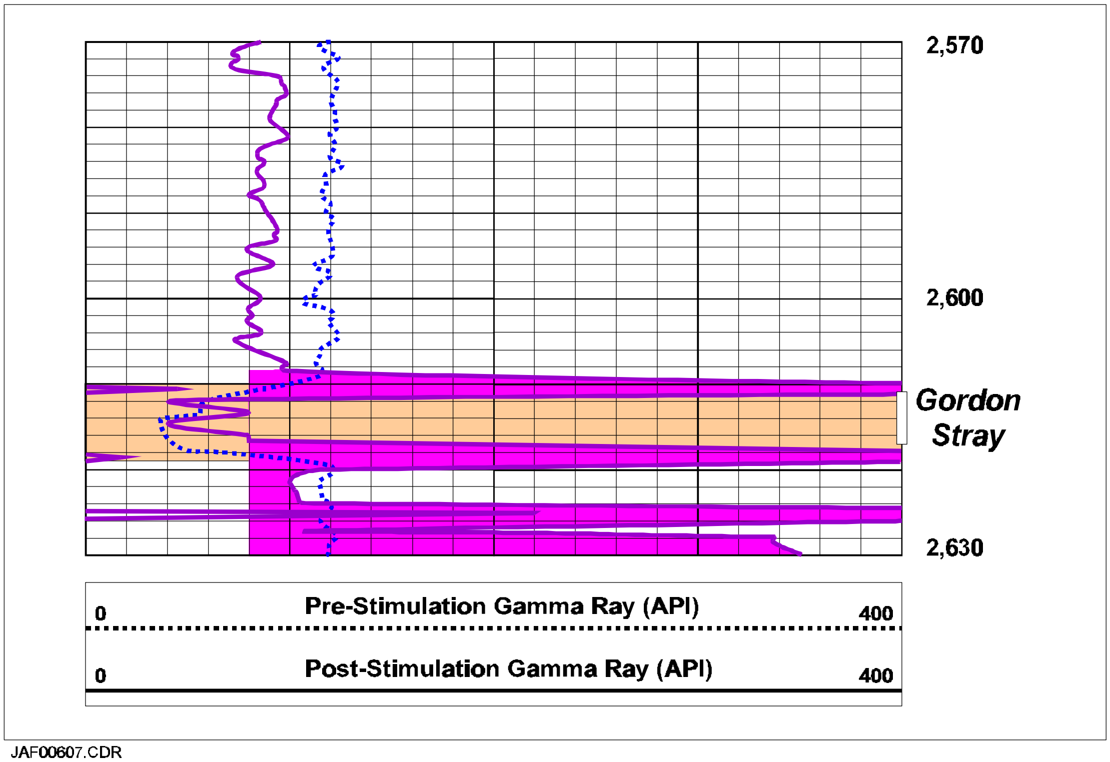

Figure 8. Donegal 4003 Radioactive Tracer Survey Results

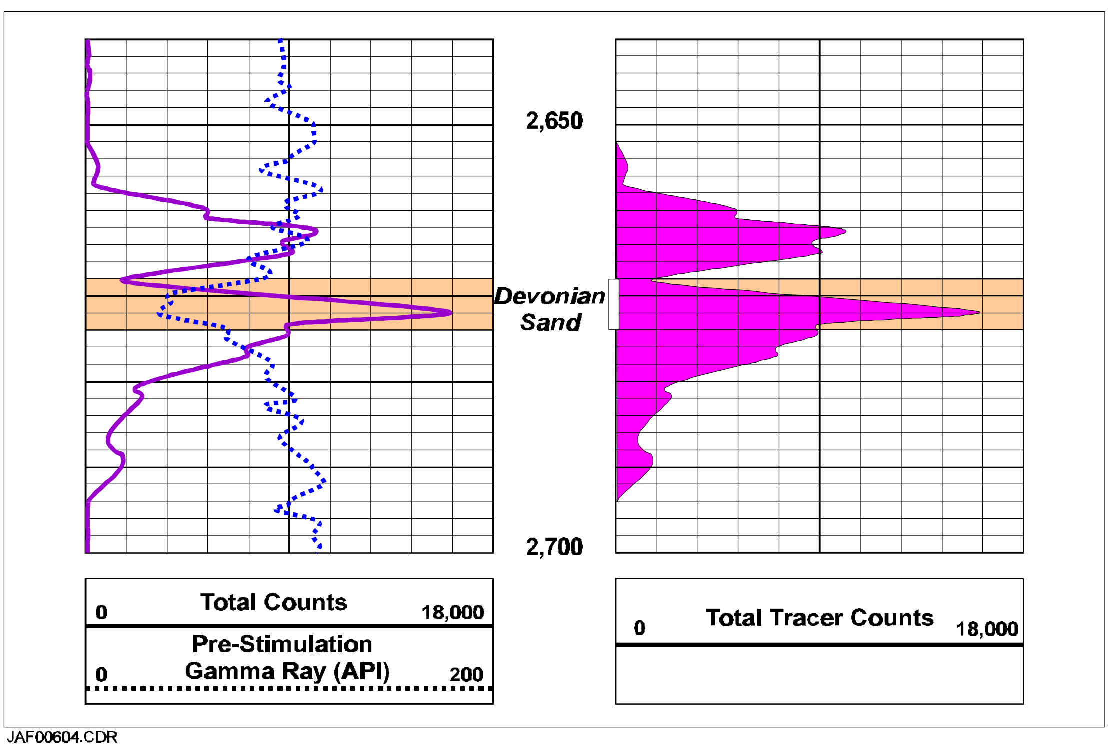

Figure 9. Donegal 4053 Radioactive Tracer Survey Results

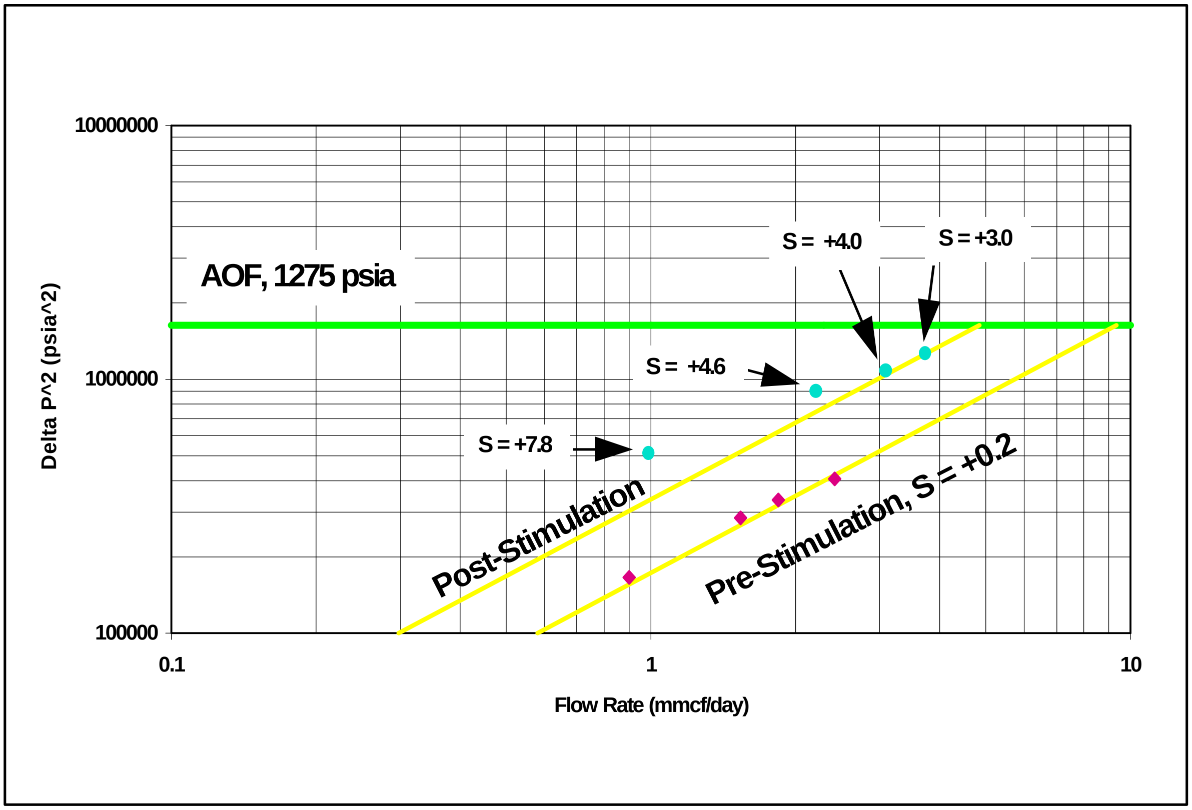

Figure 10. Well 4053 Post-Stimulation Deliverability Plot